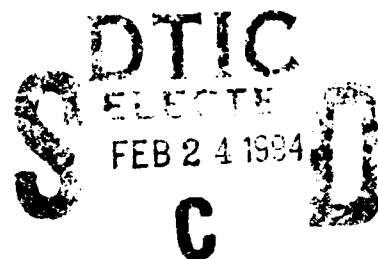




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Title: Coordination in Distributed Problem-Solving Networks
Contract #: N00014-89-J-1877
Reporting Period: April 15, 1989 - April 14, 1992



TECHNICAL PROGRESS (April 15, 1989 - September 30, 1989)

The Distributed Vehicle Monitoring Testbed (DVMT) has been significantly modified to make it a suitable vehicle for studying issues in real-time coordination among agents and more complex protocols for sharing information among agents. A prototype implementation of a multistage negotiation protocol for use in distributed resource allocation has been completed. The Partial Global Planning (PGP) coordination framework has been extended to include task allocation via contracting, and progress has been made in the design of a generic version of this protocol. Additionally, a new framework for building cooperating experts has been proposed based on negotiation as an integral part of the problem-solving framework.

A major part of the group effort over the last 6 months (contract started 4/15/89) has involved significantly extending and modifying the Distributed Vehicle Monitoring Testbed (DVMT). The purpose of this effort has been to make the testbed a more realistic model for studying distributed problem solving coordination issues. The changes have been to add:

- approximate knowledge sources; this allows the system to trade off the time to get a solution against the quality of the solution. Quality can be varied along the dimensions of precision, completeness, and certainty of the solution.
- more sophisticated, multi-level control architectures; this controller permits us to incorporate complex control strategies using BB1-style control plans and to vary the overhead of control based on the requirements of the high-level control strategy that is currently being employed.
- more complex representation of belief; a four-valued belief system has been implemented which permits us to do multi-sensor fusion of data either originating from local sensor or from partial solutions received from other agents.
- more complex and detailed domain model simulator; this permits us to generate more realistic scenarios involving ghosting and correlating signal distortions, and also to determine how signal strength decays with distance from the sensor.

These changes to the DVMT have made it a more suitable testbed for studying real-time coordination issues and more complex domain protocols for information sharing among agents.

We have also studied the problem of how to do distributed resource allocation in which there are a set of independent, high-level resource allocation goals that need to be solved in the network. Each goal can be potentially solved in multiple ways, i.e., each goal has a set of resource allocation plans, any of which can solve the goal. Each plan is composed of a set of subgoals where each subgoal is associated with a specific agent. An agent may, in turn, have



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multiple ways that local resources could be assigned to solve the subgoals; specific resource allocation plans for a subgoal can, in turn, affect the options available to other agents solving a different subgoal of the same high-level plan. Indirect interaction among subgoals of different high-level goals occur since local resource commitment for one subgoal affects the resource available to an agent for solving subgoals of other goals. We have developed an approach to this problem based on a multistage negotiation protocol. In this approach, no agent has a complete global view; each agent exchanges information on the impact of other agents' local tentative resource commitments in order to reach consistent global allocations or recognize that the problem is overconstrained and some high-level goals must be dropped in order to find a satisfactory resource allocation plan. The goal of the protocol is to minimize the exchange of information among agents. We have developed a working version of this protocol and associated network simulator to test the performance properties of the protocol on realistic examples. Two additional extensions of this negotiation protocol have also been developed: 1) to allow agents to choose goals to be given up when all goals cannot be simultaneously solved, that is, the problem is overconstrained, and 2) to guarantee that all the possible combinations of local actions in agents are tried without falling into a loop. These extensions lead to a three-phase protocol involving an asynchronous search phase, a coordinated search phase, and an overconstrained resolution phase.

We think this protocol is an important piece of work in its own right, but we are also very excited about the insights it has given us into coordinating distributed search. In future work, we hope to develop, based on this work, a theoretical framework for describing the necessary mechanism to handle interacting subproblems in a distributed search. Another important aspect of our work has involved extending and generalizing the Partial Global Planning (PGP) framework that we previously developed for network control. The partial global planning approach to distributed network control as implemented in the DVMT significantly improved the network-wide performance of cooperating nodes. It accomplished this by modifying the scheduling of local problem solving and communication activities so that: redundant activities were avoided; the generation and communication of results which could be used at other nodes was done in a timely fashion; idle processing capacity in the network was used by overloaded nodes. However, the PGP algorithms depend on the existence and availability of certain subproblem relationships present in the DVMT. Generalized partial global planning is an attempt to relate PGP to other domains, and to develop a framework for new coordination algorithms, based on a more general characterization of distributed subproblem interactions. Our goal is to develop a distributed network control mechanism that would be applicable to a wide range of cooperative distributed problem solving (CDPS) systems. Generalized PGP will be useful for ensuring globally coherent behavior in a CDPS system where each agent is able to specify at some level of detail and for some short time period the goals it intends to achieve and some approximate model of the time required to complete these goals. Our approach to this problem has been to develop a set of generic goal relationships that will allow us to plan the order of achieving goals and how results should be synthesized into larger answers. This fixed set of primitive relations will be domain independent, but for some relations the act of determining if that relation holds will be domain dependent. These relationships should also take into account the interactions among non-computational resources. A high-level protocol will allow an agent to specify and maintain its goal, plan, or task structure and transmit that structure to other agents for coordination purposes. Much like contract nets provide a domain-

independent task allocation mechanism, we are proposing to build a generic network control system that will provide support for domain independent objects (such as agents, goals, plans, and tasks) and relations among those objects. The system builder provides his domain problem solving control and his won domain relationships, as well as support for the recognition of domain independent relationships. The generic PGP system then uses these relationships to bring about coherent network problem-solving behavior, as well as providing a framework in which to build the system. The work to date has involved studying a number of different CDPS applications to understand how to characterize the goal structure of agents in these domains. This has resulted in a set of generic relationships among goals that fall into four general categories:

- Graph Relations: some generic goal relations can be derived from the graphical structure of goals and subgoals, for example, parent/child, supergoal/subgoal, overlaps, necessary, sufficient, extends, subsumes, competes.
- Temporal Relations: These are not strictly domain dependent, but do depend on the timing of goals – their start and finish times, estimates of these, and real and estimated duration.
- Domain Dependent Relations: This third set of relations is generic in that the relations apply to multiple domains, but domain dependent in the sense that they can be evaluated only with respect to a particular domain – inhibits, cancels, constrains, predicts, causes, enables.
- Non-computational Resource Constraints: One type of relation that is not dealt with by PGP at all is the use of physical, non-computational resources. This is a major part of some problem domains, such as factory scheduling and office automation.

The next phase of our research is to develop the distributed scheduling algorithms that will exploit these relationships in order to alter local agents' schedules to achieve more coherent behavior among agents. Finally, we have also made progress on developing a distributed problem-solving framework for heterogeneous cooperating experts. The major issue is how the agents resolve conflicts in their long-term knowledge source about the appropriate criteria for solutions to overlapping and interacting subproblems. The framework is based on making negotiation among agents (the recognition and resolution of conflicts) an integral part of how agents coordinate their behaviors. This work has just begun but we are very excited about its implications for designing cooperating experts.

TECHNICAL PROGRESS (October 1, 1989 - September 30, 1990)

A major focus of this last year's research efforts has been to construct testbeds that permit us to empirically explore some of the fundamental issues in Cooperative Distributed Problem Solving (CDPS): negotiation among heterogeneous agents, real-time coordination, distributed planning, resource allocation, and situation assessment. These testbeds are, respectively: 1) Cooperating Expert Systems framework and its use in a mechanical design task of building a heat-exchange pump system, 2) an enhanced version of the Distributed Vehicle Monitoring Testbed (DVMT) to permit the study of real-time coordination where agents can trade off processing time for solution optimality, 3) a multiple fireboss version of the Phoenix Fire-Fighting System, and 4) a new architecture for distributed situation assessment which allows sophisticated cooperation among agents to resolve inconsistencies and integrate multi-sensor data. It is expected that these testbeds will provide important empirical insights into the

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requirements for effective cooperation in complex, real-time distributed, problem-solving systems.

These testbeds already have produced insights into the role of negotiation in CDPS. A number of new negotiation protocols have been developed for distributed resource allocation, heterogeneous agent cooperation and distributed situation assessment. Additionally, a conceptual framework for describing the role of negotiation at all stages of problem solving has been developed. Significant progress has also been made in a design of a generic version of the Partial Global Planning (PGP) framework for network control. This progress has involved extending the architecture to overcome limitations of the earlier work which were realized during our attempts to implement the generic version. A new version of the PGP architecture incorporating these ideas is currently being implemented in the DVMT.

Since much of our effort has focused on the use of negotiation, let us first discuss its role in distributed problem solving. Some problem decompositions may involve agents with different perspectives working on the same goal or agents working on interdependent goals which share constraints or require common and limited resources for their solution (i.e., explicit or implicit interacting subproblems). Thus, agents may face conflicting solutions to tasks during problem solving; additionally, some of these tasks may involve making conflicting control decisions on what the most appropriate problem-solving organization is that agents should adhere to, what goals to focus on, which agents should solve these goals and in which order. Conflicts may arise even if the agents try to have some degree of coordination due to their lack of a global view of the problem-solving state, due to the distribution of information and limited communication bandwidth, or due to their heterogeneous expertise. Agents can deal with such conflicts through negotiation, the process by which the agents act to resolve inconsistent views and to reach agreement on how they should work together in order to cooperate effectively.

Negotiation among multiple agents involves agents reaching a consensus through the process of conflict detection, propagation, and resolution. We emphasize that negotiation may be a complex and pervasive process that is not only necessary in resolving conflicts occurring in domain problem solving but also those occurring in control problem solving. We also show that in the latter case, negotiation is not limited to only control decisions involving the allocation of tasks to agents. We examine the role of negotiation in the different stages of the problem-solving process, namely during the formulation of goals, the selection of active goals, the allocation of selected goals, the solving of these goals, and the organization of agents. This analysis has resulted in what we think is a very exciting model within which to see all the aspects of distributed problem solving.

The work on a multi-fireboss Phoenix represents to us the most sophisticated application of negotiation ever demonstrated in a distributed application. Multi-fireboss Phoenix provides a real-time environment to study cooperative planning and decentralized negotiation. Spatially distributed agents (firebosses) having only local views, negotiate to plan a globally acceptable resource configuration for fighting forest fires. This involves the planning and monitoring of the allocation of bulldozers to building firelines to retard growth of a fire. Negotiation is viewed as a distributed search through plans requiring various resource allocations, and

hence, leading to different resource configurations. The goal of the distributed search is to find a satisficing resource configuration that limits the total loss to an acceptable level while being able to be found in a reasonable time. To realize the negotiation, a three-phase framework has been created. We have developed an example scenario and initial implementation results to concretize the framework.

The unifying theme of the negotiation in this work is examining resource configurations with continuing higher loss levels. The agents first seek bulldozer distributions under the minimal fire configuration. If they cannot find a bulldozer distribution under that configuration which qualifies as a solution, they must incur more loss. The agents must then delay goals to create a new configuration. They search alternative distributions under that configuration. They may find a solution or they may have to construct a new higher loss configuration. The negotiation is structured into three phases. They represent three distinct problem-solving activities and they provide a way to coordinate the distributed search. Using the negotiation framework, different heuristics may be used to construct alternative resource configurations, characterize the search process, and create a new search level. Thus, the framework provides a means to study various negotiation strategies.

The work on the cooperating expert systems framework has focused on negotiation protocols where agents possibly have inconsistent long-term knowledge. The problem that we have been focusing on is the design of a steam condenser using four heterogeneous expert systems. Conflict can occur due to incorrect or incomplete local knowledge, different goals, priorities and solution evaluation criteria, and resource contention. It is an inevitable, and not necessarily negative, part of the problem-solving process. Conflict resolution occurs as the result of information exchange among conflict participants. This communication can provide improved robustness and balance in the integrated solution. We have specified a set of strategies which can be used to resolve conflicts. The choice of strategy, given a particular conflict situation, is itself a knowledge-based problem. Information which can be applied to this choice includes available problem-solving resources, the amount of effort that has already been expended in producing a solution, the solution's rating, an estimate of the amount of processing required to generate a new solution or to repair the current one, the dependency structure of related proposals, the importance of a particular component to the global solution, the number and type of conflicting parameters, the severity of the conflict, and the flexibility of agents involved in the conflict.

Whereas the work on cooperating experts is focused on generic domain-level protocols for resolving conflicts over the validity of partial solutions, the work in the DVMT is focused on resolving conflicts that occur because agents are making conflicting local control decisions. The DVMT also addresses the issue of real-time control and how agents can negotiate over the character of a satisficing solution that meets hard real-time deadlines. In order to look at these issues we have been continuing to make major modifications to the DVMT with respect to a node's real-time decision-making capabilities. This involves a node's ability to explicitly represent and manipulate its problem-solving goals, the criteria for their completion, the expected computational resources required, and the appropriate methods. We have also introduced a scheduling time-line into the control architecture for representing the temporal

ordering among the goals that the system is currently pursuing. Also, a scheduler is being developed that recognizes and reacts to overconstrained situations.

Finally, we have developed a new testbed for doing research in distributed situation assessment. This testbed is designed to look into issues of how individual nodes, each pursuing their own interpretations, can work together to arrive at a globally consistent solution. Each node is sophisticated in its ability to symbolically reason about the current uncertainties in its interpretation and how to exploit information from nodes with overlapping and adjacent sensed areas so that its local inconsistency can be resolved and a globally consistent solution can be arrived at. In summary, we feel that these testbeds allow us to begin to empirically explore some of the key issues in building cooperating problem-solving systems.

TECHNICAL PROGRESS (October 1, 1990 - September 30, 1991)

This research studies how a network of cooperating, semi-autonomous agents, each capable of sophisticated problem solving, can coordinate their actions and interactions to work as an effective team. The development of coordination mechanisms that achieve coherence among homogeneous and heterogeneous agents' activities is based on three guiding principles. The first is to make local control in each agent more sophisticated so that available information about the local search is better utilized. The second is for agents to exchange meta-information about their local search space so that local control decisions can be made in the context of a more comprehensive view of the composite search space. In our experience, these first two principles are complementary since the better the local control strategy is in understanding its own search space the easier it is to construct meta-information that abstractly represents the key aspects of its search space that are important to another agent. In a similar vein, local control must have a certain level of sophistication in order to exploit the meta-information about other agents' search spaces. The third principle is satisficing control in which significantly reduced computational costs to implement cooperative control is traded off for less than optimal but still acceptable levels of coordination among agents.

During the first year and a half of the contract, our emphasis was on developing new testbeds that would be appropriate for studying the following CDPS issues: negotiation among heterogeneous agents, real-time coordination, distributed planning, resource allocation, and situation assessment. These testbeds are, respectively: 1) Cooperating Expert Systems (CEPS) framework which provides a comprehensive framework for heterogeneous, cooperating experts to work together to arrive at acceptable solutions in spite of inconsistencies in their long-term knowledge and criteria for acceptable solutions; 2) an enhanced version of the Distributed Vehicle Monitoring Testbed (DVMT) to permit the study of real-time coordination where agents can trade off processing time for solution optimality; 3) a multiple fire-boss version of the Phoenix Fire-Fighting System; and 4) a new architecture, DRESUN, for distributed situation assessment which allows sophisticated cooperation among agents to resolve inconsistencies and integrate multi-sensor data. The DRESUN architecture also provides techniques for distributed differential diagnosis and graceful degradation of solution quality in face of hardware failure and real-time deadlines. This architecture significantly extends the technology available for designing distributed situation assessment systems.

In this past year, we have made significant progress in completing sophisticated applications for these testbeds. We have implemented and begun evaluation of a number of new negotiation protocols for heterogeneous agent cooperation, distributed resource allocation, and distributed situation assessment. A cooperating experts system, TEAM, for designing a heat-exchange pump with six experts has been implemented based on negotiation among experts to reach satisficing solutions. Multiple fire-bosses are able to negotiate over the redistribution of bulldozers when a fire-boss's local resources for fighting a fire are insufficient. One of the major intuitions we have already gained in this experimental work on cooperating experts and multi-fireboss Phoenix is the need for negotiation to be sensitive to the stage of problem solving and the available solutions in an agent.

We have designed a negotiation protocol, DENEGOT, that reflects this intuition. DENEGOT is a decentralized distributed planning model which bases conflict resolution on negotiation. Negotiation is viewed as a distributed search through potential compromises. The model assumes that a satisficing solution is acceptable, a reasonable assumption in many complex domains. In our conceptualization, constraints define a standard of solution acceptability. The negotiation model consists of three iterative problem solving phases: coordinated search, negotiation state analysis, and constraint relaxation. During negotiation, agents search for a mutually acceptable compromise that qualifies as a solution to the conflict under the current constraint set. If the agents are unable to reach a solution under that constraint set, constraints are relaxed thereby enlarging the set of compromises that qualify as a solution to the conflict. Agents can then search under the relaxed constraint set. Thus, we view negotiation as an iterative process. We are also trying to more clearly formalize the structure of the solution space of an agent and how that relates to the type of negotiation and when negotiation is used.

A complicated scenario involving distributed differential diagnosis has also been implemented in DRESUN. The key in DRESUN to achieving the necessary complex and dynamic interactions between agents is to make the solution convergence process explicit. In our approach, this has been done by giving each agent an explicit representation of the goals that must be satisfied in order to meet the criteria for termination of (global) problem solving. Termination criteria that are not satisfied or have not been verified as satisfied, are viewed as sources of uncertainty about the global correctness of local solutions. Goals representing the need to resolve these uncertainties are posted and drive the overall problem solving process. Communication between agents results from the agents taking actions to meet these goals. Because the goals are explicit and detailed, communication between agents can be very directed. That is, instead of simply exchanging information about partial solutions, agents communicate specific evidence that can be used to satisfy goals of resolving particular uncertainties. Another way of viewing our approach is that we have made explicit the need to enforce constraints between possibly interdependent subproblems of the agents. We recognize (possibly) interdependent subproblems and post goals to resolve uncertainty about whether the relevant partial solutions are consistent. This latter work shows that complex multi-agent situation assessment protocols naturally arise from having sophisticated agents that can reason symbolically about uncertainties in their local interpretations of the current situation.

Progress has also been made in a design of a generic version of the Partial Global Planning (PGP) framework for coordination control. Significant limitations of the earlier work were

realized when the DVMT was enhanced. A first version of the generic PGP architecture incorporating these ideas is now running in the enhanced DVMT. We have also developed a simulation system that will allow us to empirically explore how task characteristics affect the appropriateness of different coordination strategies. Additionally, a distributed search model has been developed that explains the need for specific types of coordination among agents based on the type of control and solution uncertainty that arises in the local searches of each agent.

Summary of Technical Results (October 1, 1991 - April 14, 1992)

This research has studied how a network of cooperating, semi-autonomous agents, each capable of sophisticated problem solving, can coordinate their actions and interactions to work as an effective team. The development of coordination mechanisms that achieve coherence among homogeneous and heterogeneous agents' activities is based on three guiding principles. The first is to make local control in each agent more sophisticated so that available information about the local search is better utilized. The second is for agents to exchange meta-information about their local search space so that local control decisions can be made in the context of a more comprehensive view of the composite search space. In their experience, these first two principles are complementary since the better the local control strategy is in understanding its own search space the easier it is to construct meta-information that abstractly represents the key aspects of its search space that are important to another agent. In a similar vein, local control must have a certain level of sophistication in order to exploit the meta-information about other agents' search spaces. The third principle is satisficing control in which significantly reduced computational costs to implement cooperative control is traded off for less than optimal but still acceptable levels of coordination among agents.

During the first half of the contract, their emphasis was on developing new testbeds that would be appropriate for studying the following Cooperative Distributed Problem-Solving (CDPS) issues: negotiation among heterogeneous agents, real-time coordination, distributed planning, resource allocation, and situation assessment. These testbeds are, respectively: 1) Cooperating Expert Systems (CEPS) framework which provides a comprehensive framework for heterogeneous, cooperating experts to work together to arrive at acceptable solutions in spite of inconsistencies in their long-term knowledge and criteria for acceptable solutions; 2) an enhanced version of the Distributed Vehicle Monitoring Testbed (DVMT) to permit the study of real-time coordination where agents can trade off processing time for solution optimality; 3) a multiple fire-boss version of the Phoenix Fire-Fighting System; and 4) a new architecture, DRESUN, for distributed situation assessment which allows sophisticated cooperation among agents to resolve inconsistencies and integrate multi-sensor data. The DRESUN architecture also provides techniques for distributed differential diagnosis and graceful degradation of solution quality in face of hardware failure and real-time deadlines. This architecture significantly extends the technology available for designing distributed situation assessment systems.

During the second half of the contract that is now completed, they made significant progress in completing sophisticated applications for these testbeds. They have implemented and evaluated a number of new negotiation protocols for heterogeneous agent cooperation,

distributed resource allocation, and distributed situation assessment. A cooperating expert system with six experts, called TEAM, has been implemented in CEPS for designing a heat-exchange pump. Extensive experimentation has been done in this testbed showing the importance of the organizational structure, default assumptions, and highly tailored negotiation strategies for speeding up the negotiation process. For example, it has been shown that even though agents may be able to be both proposers and critics, agents which have underconstrained search spaces relative to other agents should take on only the role of critics. In the multiple fire-boss version of Phoenix, fire-boss agents are able to negotiate over the redistribution of bulldozers when a fire-boss's local resources for fighting a fire are insufficient. As a result of this negotiation, agents may delay fighting a fire, or fight it with few resources, in order to provide resources to the requesting agent. It is also possible that a requesting agent may change its own plans to facilitate another agent's being able to loan resources with minimal disruption to their plans. Knowing when to make these choices in the negotiation process and determining their specific character may require sophisticated reasoning. This has led to one of the major intuitions gained in this experimental work on TEAM and multi-fireboss Phoenix; negotiation needs to be sensitive to the stage of problem solving and the available solutions in an agent.

They have designed a negotiation protocol, DENEGOT, that reflects this intuition. DENEGOT is a decentralized distributed planning model which bases conflict resolution on negotiation. Negotiation is viewed as a distributed search through potential compromises. The model assumes that a satisficing solution is acceptable, a reasonable assumption in many complex domains. In their conceptualization, constraints define a standard of solution acceptability. The negotiation model consists of three iterative problem solving phases: coordinated search, negotiation state analysis, and constraint relaxation. During negotiation, agents search for a mutually acceptable compromise that qualifies as a solution to the conflict under the current constraint set. If the agents are unable to reach a solution under that constraint set, constraints are relaxed thereby enlarging the set of compromises that qualify as a solution to the conflict. Agents can then search under the relaxed constraint set. Thus, they view negotiation as an iterative process. They are also trying to more clearly formalize the structure of the solution space of an agent and how that relates to the type of negotiation and when negotiation is used. They have also explored the more general issue of the role of negotiation at all stages of cooperative problem solving. This has resulted in the specification of a generic model for negotiation called the Recursive Negotiation Model (RNM). This research, together with negotiation frameworks developed from the two applications, has provided an understanding of negotiation which they believe will allow a general computational framework (shell) to be built for facilitating the implementation of negotiating agents.

A complicated scenario involving distributed differential diagnosis has also been implemented in DRESUN. The key in DRESUN to achieving the necessary complex and dynamic interactions between agents is to make the solution convergence process explicit. In their approach, this has been done by giving each agent an explicit representation of the goals that must be satisfied in order to meet the criteria for termination of (global) problem solving. Termination criteria that are not satisfied or have not been verified as satisfied, are viewed as sources of uncertainty about the global correctness of local solutions. Goals representing the need to resolve these uncertainties are posted and drive the overall problem solving process.

Communication between agents results from the agents taking actions to meet these goals. Because the goals are explicit and detailed, communication between agents can be very directed. That is, instead of simply exchanging information about partial solutions, agents communicate specific evidence that can be used to satisfy goals of resolving particular uncertainties. Another way of viewing their approach is that they have made explicit the need to enforce constraints between possibly interdependent subproblems of the agents. Agents recognize (possibly) interdependent subproblems and post goals to resolve uncertainty about whether the relevant partial solutions are consistent. This latter work shows that complex multi-agent situation assessment protocols may naturally arise from having sophisticated agents that can reason symbolically about uncertainties in their local interpretations of the current situation.

Progress has also been made in a design of a generic version of the Partial Global Planning (PGP) framework for coordination control. Significant limitations of the earlier work were realized when the DVMT was enhanced. A first version of the generic PGP architecture incorporating these ideas is now running in the enhanced DVMT. They have also developed a simulation system that will allow them to empirically explore how task characteristics affect the appropriateness of different coordination strategies. This simulation system also allows the exploration of issues involved in real-time deadlines among cooperative agents. Interesting empirical results on the importance of specific coordination strategies in overloaded situations have been developed based on this simulation system. As a result of this work, they have begun to understand how real-time issues can be accommodated in coordination strategies. This has resulted in a revised model for coordination in which the basic role of the coordination strategy is to recognize relationships among its tasks and those of other agents. These relationships are then translated into constraints that are passed to the local real-time scheduler in each agent. When constraints cannot be implemented in the local schedule, the local scheduler passes this information back to the coordination module together with possible meta-information about the schedule. The local coordination module, through interactions with coordination modules in other agents, decides how to revise these violated constraints and then passes these revised constraints to its local scheduler. Additionally, a distributed search model has been developed that explains the need for specific types of coordination among agents based on the type of control and solution uncertainty that arises in the local searches of each agent.

As a result of this three-year research effort, significant progress has been made in understanding the role and mechanisms needed for supporting negotiation and real-time coordination among cooperative agents.

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